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Life Cycle Assessment of Network Traffic: A Review of Challenges and Possible Solutions

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Abstract: The environmental impact of Industry 4.0 and related technologies remains relatively unknown, with little research devoted to investigating the impact on sustainability aspects, resulting in a greater need for climate reporting. However, impacts of data transmission have historically been the least studied part of the information and communication technology sector, and there is currently no consensus on how to correctly assess it. In an attempt to guide process development within the area in the hopes that future life cycle assessments will be created, this study sought to identify, examine, and address potential challenges that might occur when assessing the environmental impact of network traffic during its life cycle. Through a combination of a literature review and semi-systematic research interviews with identified experts within the field of research, several areas in the form of knowledge gaps, unsolved methodological issues, and areas in need of further development were identified and assessed. The results show that eight key challenges exist in the areas of system boundaries, data collection methods, energy intensity metrics, transparency and data availability, age of data, allocation procedures, assumptions, and limited coverage of impact categories. Several approaches to address said challenges are presented, as well as areas in need of further investigation. It is furthermore suggested that the sector should strive to agree upon several parameters of significance to enable future harmonized life cycle studies of network traffic.

Keywords: life cycle assessment; LCA; network traffic; data traffic; data transmission; challenges; environmental impact; ICT; electricity intensity

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1. Introduction

The evolution of Industry 4.0 and related technologies such as the Internet of Things and big data analytics carry high expectations to enable transition to a more environmentally sustainable society. However, the impact on the environment of information and communication technology (ICT), which is crucial in achieving this development, is still largely unknown, with little research devoted to investigating the impacts [1,2]. Only sparse research exists that comprehensively evaluates the environmental impact of the ICT sector with all elements included [3]. For instance, many case studies lack information regarding the impacts of user equipment and Internet data services, and the impacts of network transmission itself has historically been the least studied part of the whole sector [4]. In the few studies that exist, the magnitude of energy intensity varies by a scale as large as 20,000, indicating that the assessment of internet transmission is a complex task. It is often a controversial subject of discussion [5], and there is currently no consensus on how to correctly assess the environmental impact of network traffic.

Life cycle assessment (LCA) is increasingly used for comprehensive assessment of the environmental impact of ICT. LCA is a well-established tool to measure potential environmental impacts of products or services throughout their life cycle, from raw material extraction to final waste disposal [6]. An increasing amount of studies on the topic of LCA and network traffic have been published in recent years [7–13], however, they all wrestle with challenges in the form of knowledge gaps, unsolved issues and methodological differences remain that hinder development within the area of network traffic, with few systematically trying to define these challenges [3,4,14]. For example, many studies use different terminology to explain the included subsystems, and the difficulty to define appropriate system boundaries is often mentioned as a result of a too complex system [5,15–17]. Several articles also mention the subject of data availability, where the lack of sufficient data along networks and data centers creates great difficulties for the LCA practitioners [12]. An extensive data collection methodology is required, which currently can be conducted in several different ways, resulting in a variety of methods that greatly influence the results [15,16,18]. Furthermore, several articles mention the importance of the age of the collected data as a result of rapidly changing technology [4,15]. The assumptions and decisions made by the practitioners in an inventory are also indicated to significantly impact the result [17,18]. As the demand for LCAs is growing among consumers and investors and they are becoming more widely used by organizations for policy making, among other things, the consensus regarding the methodological decisions within LCA calculations become increasingly vital. Without harmonization, the results risk becoming incomparable, and the decisions based on the LCAs less meaningful. To the best of our knowledge, no current study exists that has summarized all existing challenges linked to the research field of network traffic and its life cycle impact.

This paper presents an exploratory study which aims to identify challenges in the form of knowledge gaps, unsolved methodological issues, and areas in need of further development when assessing the life cycle environmental impact of network traffic. We also propose how these challenges can be addressed, in an attempt to guide methodological development, in the hopes that future life cycle assessments in this field will be will become more harmonized and reliable. The results presented in this paper are based on a thesis by Billstein [19].

The rest of this paper is structured as follows. Section 2 describes the chosen approach and applied methodology. Section 3 presents the evaluation procedure and the obtained results. Section 4 discusses the findings, the applied methodology, and areas in need of further research. Section 5 presents our concluding statements.

2. Methodology

An exploratory, qualitative research method approach was adopted to identify challenges for assessing life cycle impacts of network traffic and potential solutions. First, a literature review was performed to identify challenges that have been identified and discussed in previous studies. Among the challenges identified in the literature, the seemingly most significant ones were selected based on their reoccurrence in the literature. These were discussed further in semi-systematic qualitative interviews with experts within the field, where both challenges identified from the literature review, possible solutions, and potentially new challenges were discussed. Based on the literature review and input from the interviewees, a list of current challenges was identified, and potential solutions and research directions were outlined and discussed. The included steps are summarised in Figure 1.

Figure 1. Overview of the included steps in the study.

2.1. Literature Review

The literature review followed the principles outlined in Snyder (2019) [20], with an unstructured search query followed by a structured search in Scopus, Web of Science, and Google Scholar for articles containing the search terms *data traffic*, *network traffic*, *environmental impact*, *LCA*, *ICT*, and *energy intensity*. Iterative snowballing was performed to complement the initial search with further relevant literature [21], with the purpose of identifying literature that mention challenges linked to measuring the life cycle impact of network traffic. The search was performed during the period 8 February–4 March 2021, and only peer-reviewed articles in English and published after 2004 were included.

2.2. Semi-Systematic Qualitative Research Interviews

Interviews were held with eight experts in the field of ICT, LCA, and/or network traffic (Table 1) after being identified as key individuals either via examined research articles or by recommendations. The interviews were conducted in the form of semi-systematic qualitative research interviews [22], with a written interview guide prepared prior to the interviews (Appendix A). The interviewees were asked the same key questions listed in Appendix A; however, the questions did not always follow the given order nor were they asked with the same specific phrasing during each interview. Follow-up questions and probing questions were also asked to gain further insight into interesting topics or when answers needed to be clarified. All interviews were conducted in the form of video meetings, which were video recorded in agreement with the interviewees. The chosen participants were informed, both by email beforehand and orally during the meeting, about the purpose and structure of the interviews. They were also given the opportunity to be anonymous, to which one person agreed. Before finalization, they were given drafts of their contributions to verify their oral statements. The interviews took place between the dates of 2021-03-18–2021-03-31 and were conducted in English or Swedish.

Table 1. Interviewees partaking in the semi-systematic qualitative research interviews.

Respondent	Name	Title	Organization
Interviewee 1	Roland Hischier	Head of Advancing LCA Group	EMPA
Interviewee 2	Dag Lundén	Environmental Manager	Telia Sverige AB
Interviewee 3	Sara Gorton	Head of Environmental Strategy	Telia Sverige AB
Interviewee 4	Vlad Coroama	Senior Research Associate with Institute for Pervasive Computing	ETH Zürich
Interviewee 5	Lorenz Hilty	Professor of Informatics and Sustainability	UZH University of Zurich
Interviewee 6	Jens Malmodin	Senior Specialist Environmental Impacts and Life Cycle Analysis	Ericsson
Interviewee 7	Pernilla Bergmark	Principal Researcher ICT Sustainability Impacts	Ericsson
Interviewee 8	Anonymous	Senior Life Cycle Expert	Telecom company

3. Results

The literature review identified eight possible challenges of measuring the life cycle impacts of network traffic. Three of these were confirmed and commented on by all interviewees as being of significant importance, while the rest were met by recognition in all but two interviews each at most, deeming all eight challenges of high relevance. These are summarised in Table 2 and described in further detail in the following sections. Six other challenges were brought up for discussion by the interviewees. However, none of these reoccurred in more than two interviews in total or previously during the literature review. Therefore, they were not deemed significant enough for further investigation.

3.1. Challenge 1: System Boundaries

There is currently no standardized way of categorizing the components of network transmission. Therefore, the definition of system boundaries and the choice of included subsystems has been deemed the most important methodological decision [11]. Several approaches to defining the system and its system boundaries have been used [10,11,17,23] in LCAs of network traffic, with quite significant differences, rendering the results incomparable [11,24]. As a result, a commonly accepted delimitation of system boundaries and included sub-systems needs to be developed to enable the comparability of future studies, which was further confirmed by the interviews. Several reasons were also mentioned as to why the system boundaries continue to differ between studies, including the complexity of the ICT sector in the form of a large number of involved stakeholders on a global level [25], the gap in knowledge among involved actors which has resulted in flawed images of the system [26], the inclusion of ever-changing components [25], and the different backgrounds of researchers [27].

Table 2. Identified challenges during the literature review and interviews.

Challenge	Literature Review	Interviews
System boundaries	X	X
Data collection methods	X	X
Measurement units for electricity intensity	X	X
Transparency and data availability	X	X
Age of data	X	X
Allocation procedures	X	X
Assumptions during the life cycle inventory phase	X	X
Limited coverage of impact categories	X	X
Differing degree of knowledge among practitioners		X
Other functional units in media		X
Less focus on mobile networks than fixed		X
Less focus on production phase than use phase		X
Different and differently validated models		X
Low understanding among the public		X

A necessary step towards a common agreement on a standardized set of system boundaries is to map and compare current versions. Several articles were identified that illustrate the system boundaries used in the particular studies [10,11,17,23], and three articles were also found that compare system boundaries between selected studies [5,11,16]. Figure 2 illustrates the five most commonly used system boundaries (alternatives A–E) and included key components, based on the literature [10,11,17,23] and input from the interviewees [25,28], who were given the opportunity to comment on its accuracy to improve its validity and representativeness. Alternatives C and E were identified by the interviewees [25,27–31] as the most representative conceptual illustrations of how the network traffic system should be modelled and measured when quantifying the environmental impact of network traffic.

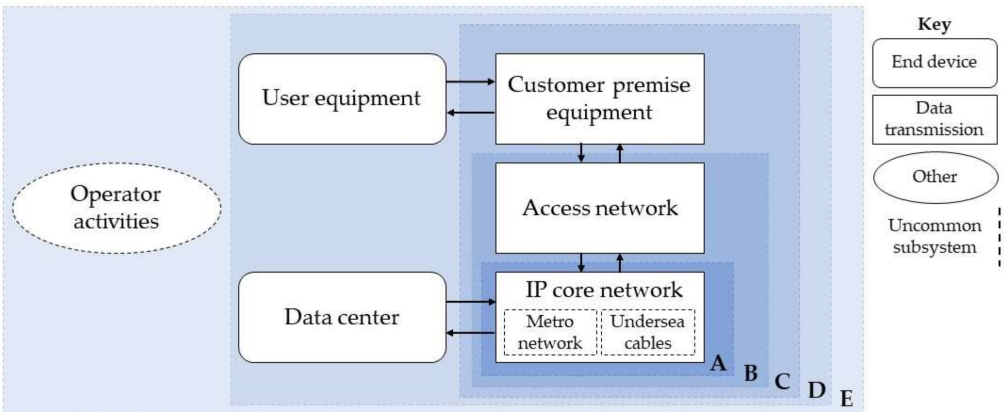

Figure 2. Different combinations of system boundaries identified in previous studies.

Interviewees favouring alternative C argued that the remaining subsystems should be differentiated from the rest [27,28], and it was suggested that the system instead should be modelled as three main modules; user devices, network equipment (alternative C), and data centers. This would allow the LCA practitioner to collect data for the sub-systems and combine them based on the aim of the study [28].

3.2. Challenge 2: Data Collection Methods

When estimating the life cycle impact of network traffic, measuring, and collecting accurate data has been proven to be difficult due to the size and complexity of the ICT sector and its supply chain [3,12]. As a result, there is a risk of increased use of generic data which in turn may add to contradicting results between LCAs [24]. Several data collection and calculation methods exist [5,11,32,33], which are known to be flawed [11,17,33,34] and the diverging usage of them could further increase the gap between the results, rendering them incomparable. Therefore, a better approach for measuring and collecting data in future studies needs to be identified. During the interviews, it was further validated that several data collection methods exist, whereof the top-down method and the bottom-up method were found to be most reoccurring. In relation to energy intensity, the top-down method has been defined as measuring and dividing the total electricity consumption of the Internet or traffic for a region with a defined time, yielding an average number of the energy consumption per data transferred [11,33]. Flaws were mentioned by several interviewees, including large overestimation errors [11], too wide system boundaries [28], and allocation problems that occur when a large amount of activities must be sorted [27,29]. In comparison, the bottom-up method is defined as direct observations from one or several individual case studies [5], i.e., the sum of electricity consumption at equipment level divided by the amount of data transferred [11]. The approach is leaner [17], often leading to underestimations [11], and there is a risk that vital equipment is missed [17] due to too narrow system boundaries [28].

A necessary step towards avoiding contradicting results is to determine the best currently existing approach for measuring and collecting data. A consensus was found among the interviewees that a combination of the top-down and bottom-up methods to validate each other would be most appropriate [25,27,28]. As flaws where identified with both methods, it was furthermore discussed whether improvements could be made. Whether it is possible remains to be seen, however, as it would depend on the specific additions made [28]. It was furthermore noted that future improvement of the two methods may implicitly happen in the future by itself. Therefore, it was suggested that LCA practitioners not should aim to improve the methods but rather aim to be consistent in the way the current methods are used [27]. Lastly, it was noted that data should be collected from operators to the largest extent possible, as theoretical models (i.e., based on theoretical numbers) should be avoided due to their complexity [30].

3.3. Challenge 3: Measurement Units for Electricity Intensity

There is currently no standardized way of measuring the average electricity intensity, i.e., the measurement of data transmission [5,11]. As a result, three different measurement units commonly occur in studies: energy per data, energy per time, and energy per subscriber [3,5,10,11,16,32], which was further confirmed by the interviews [27,28]. The importance of choosing the correct metric has been highlighted in several studies [11,35], as the results of LCAs continue to differ widely, weakening the robustness of any conclusions drawn from the results [17].

A necessary step towards an agreement on the correct energy intensity metric is to determine in which scenarios the different metrics are most appropriate. Results from the interviews indicate that the choice of metrics should depend on the type of subsystem in question [27,28,30], i.e., if a device were to use the same amount of electricity regardless of the load, it should be measured based on time. If the energy consumption instead were to be proportional to the load, the device should be calculated per data volume [27]. Several interviewees, therefore, argued that the IP core network should be modelled using the unit energy per data [27,28], whilst the access network, customer premise equipment, and end-user devices fall under the category of energy per time [28,30].

3.4. Challenge 4: Transparency and Data Availability

There is currently low transparency within the particular research field, i.e., a lack of published data and methodological descriptions [3,12]. Therefore, LCA practitioners risk having to make further assumptions or adopt data from past studies without detailed analyses of the underlying assumptions, which might jeopardize the representativeness of future LCAs [24]. The information currently available is furthermore often found to be not fully comprehensive [3] and more transparent and sufficient data linked to the networks and data centers are thus needed [12]. During the interviews, the low transparency within the research field was confirmed and several causes to the challenge were also identified, including a competitive market [27], lacking scientific validation processes [28], and more pressing issues within the sector (e.g., IT security issues) [27] and word limits of research papers which do not support a detailed disclosure of studies of complex products and systems [26].

To improve the transparency and increase the amount of published data and methodological descriptions, areas in need of further development need to be identified. Previous studies have highlighted a better stakeholder involvement as a necessity [5], as well as more transparent and up-to-date inventory data of the use phase of ICT-related devices [12]. Results from the interviews indicate that the low stakeholder involvement is a matter of maturity of the market, with one participant observing market developments that indicate that stakeholders are becoming increasingly aware of the benefits of sharing data, i.e., becoming more transparent [25] while another had observed an increased request for transparency related to sustainability, which could benefit the willingness to share data positively [26]. However, due to increasing demands for the ICT sector's environmental impact, time is of the essence [28]. A possible implementation of a separate entity within the ICT sector, acting as an independent and trustworthy third party collecting information from relevant stakeholders, could be implemented to enable a more transparent and up-to-date inventory data of the usage phase. However, the idea was deemed unrealistic by several interviewees [25,27], who argued that its purpose would be too specific, there is no market interest in such facility, and that it should not be a requirement to share such knowledge, but that it instead should be given free of will [25].

3.5. Challenge 5: Age of Data

Increased developments within technology and improved equipment, e.g., in the form of energy efficiency gains in transport equipment, have a significant impact on the results of recent studies of network traffic [5], and researchers have made a point of clarifying to what exact year the data is referring to in an attempt to be as transparent as possible [11,32]. The technological improvements have furthermore resulted in a need to continuously update previous estimates [9]. The challenge was further validated by the interviews, where technology and the age of data, as well as necessary solutions, were discussed.

A necessary step towards minimizing the effects of rapidly changing technology is to identify how LCAs can be compared. One article suggested limiting the validity of the results to the year of reference of the data [5], which was deemed a reasonable time interval during the interviews if LCA practitioners seek to compare trends over time [25]. However, it was also argued that data from life cycle inventory (LCI) databases often include old and outdated information [29] resulting in poor and inaccurate data quality of the studies [25]. Another interviewee found that a comparison of LCAs based on their year of reference could be applied to some extent hypothetically if other parameters in the study were to be similar enough. However, it was argued that the year of reference would not inform a comparison of studies sufficiently without an analysis of the age of different data points, which may vary considerably [26]. It was also suggested to compare LCA studies via the efficiency gains in the equipment rather than by the year of reference [27,28]. However, how plausible the solution is remains to be seen due to the alleged difficulty of making such estimations [30].

3.6. Challenge 6: Allocation Procedures

Multifunctionality has been deemed particularly difficult to handle in relation to network traffic due to the complex infrastructure and usage practices [3], resulting in a wide variety of possibilities [12], resulting in major variations. The interviews confirmed the challenge of multifunctionality in relation to network traffic and several areas were furthermore identified as being particularly difficult to allocate, including the endpoints of data transmission (i.e., user devices [25,28] and data centers [27,28]) where a division must be made between the many components which use network traffic, as well as the unused capacity in networks [25,27]. The latter occurs when LCA practitioners seek to allocate the unneeded capacity of the network from periods where there is a gap between the average daily load and capacity installed [27].

A necessary step towards minimizing the variety of possibilities when dealing with multifunctionality is to determine appropriate allocation procedures in the areas identified as particularly difficult. Several interviewees suggested dividing the different services of user devices with an allocation method based on time [27,30], however, the method should not be based on assumptions or one single use case since it could result in a non-realistic number [25]. Several interviewees also suggested that unused capacity in networks could be solved by dividing the energy evenly among all users [25,27], either by gigabyte or by the chosen functional unit in the study [27]. However, the suggestion was deemed non-trivial [25]. It was also noted that an allocation problem likely will occur in data centers [27,28], although relatively few comments and insights on this topic could be gained.

3.7. Challenge 7: Assumptions during the LCI Phase

Varying assumptions during the LCI phase in studies of network traffic have been identified as an important source of differing results among studies, as decisions made at the inventory level significantly influence the results [18]. For instance, assumptions on the number and energy efficiency of routers and optical transmission equipment [10] and assumptions regarding parameters with significant geographic variability, such as the electricity mix or recycling quotas [12] have been identified as important sources of variation in results among studies. Past studies, furthermore, often lack detailed analyses of the underlying assumptions made [17]. This was confirmed as a challenge during the interviews, where several areas in the LCI phase, with differing and/or lacking assumptions, were identified to influence to a larger degree. These areas also reoccurred in literature, including the choice of electricity mix [18,27] and choices made during the data collection methods [29]. For instance, when collecting bottom-up data, the researcher must determine the weight of the included devices, the rough data input, their energy usage, how much of the data goes through the equipment, and the lifespan of the devices [24], as well as the number of included devices and the renewable energy sources used [22]. When this information is missing, assumptions have to be made regarding these parameters. During the top-down method, other assumptions must instead be made regarding how long the equipment is used and their replacements, for which bottom-up data also often required to substantiate the information [22].

A necessary step towards more consistent assumptions during the LCI phase is to identify the most appropriate choices that could be made within the areas of highest significance. When discussing assumptions concerning the electricity mix, one interviewee suggested a local electricity mix for user premise and end-user equipment and a world average for the data transfer [27]. However, problems with this approach were raised by another participant who argued that the average mix may not always be representative, as many operators produce or purchase renewable electricity. Hence it would not be fair to use the worldwide average carbon intensity of electricity usage [28]. Continued, more transparent sensitivity analyses was also identified as a key aspect to determine appropriate assumptions within the other areas [29].

3.8. Challenge 8: Limited Coverage of Impact Categories

The limited coverage of impact categories was identified as a challenge, as nearly all studies on the environmental impact of network traffic focus only on the carbon footprint [9–11], thereby leaving out other impacts of importance to the industry, such as impacts on water and land [9]. Hence, the complete environmental impact of network traffic within all impact categories is rarely assessed. The interviews confirmed the limited coverage within other impact categories and several causes were identified as to why full LCAs are less common than carbon footprint studies, including the pressing matter of climate change [26,28,36] and a need to please the media [27]. It was also found that results often originate from researchers with more experiences within the world of ICT than in the field of the environmental sciences and its related methods, including LCAs [28]. Furthermore, climate and energy were identified to have a clearer basis for the underlying calculations, compared to other categories which contain non-consistencies [29]. Therefore, the low number of environmental scientists within the research field, as well as lack of knowledge regarding LCAs [28], described by another interviewee as a shortage of LCA resources [26], were deemed to affect to some degree. Lastly, it was argued that the origin of the research field could be a potential reason, since it first originated from the perspective of studying the usage phase of network traffic wherein energy is the main problem and carbon its main culprit [27].

It was found that further knowledge of life cycle assessments within the research field is needed [28], which one interviewee noted may resolve in due time as more researchers conduct quantitative research and build in depth knowledge, as well as young graduates joining the research field [26]. A clearer baseline for calculations within the other impact categories was also deemed a necessity by one interviewee [25], as well as the need for a consensus among researchers on how to do it correctly, which generally can be applied to all transfers between LCI data and LCIA impacts and not just within the ICT sector [26].

4. Discussion

Based on a literature review and interviews with experts in the field, this study was able to identify eight key challenges in need of further development to harmonize data and methodological choices in LCAs of network traffic.

Since there was little prior research on the topic, a research approach combining literature review with qualitative semi-systematic interviews was selected. It allowed for a more unstructured approach, suggested by [37]. The literature review was the primary source of information when identifying challenges, using information from the interviews as a complement to confirm and nuance results of the literature review. On the other hand, in order to explore solutions, only sparse information could be found in the literature review, while more information was collected from the interviews. A methodological challenge of this study was to reach adequate coverage of the literature and in the collection of experiences among experts. Although the literature review was not an all-exhaustive systematic review, its coverage is likely adequate due to its iterative design and snowballing. Although a limited number of interviewees were included in the study, they were selected among renowned experts in the field, from both industry and academia, and covering different areas of competence related to LCA of network traffic. Thus, it is not likely that a more extensive study would discover more challenges. The interviewees confirmed the same challenges being brought up in several articles, but no interviews or articles led to new challenges, indicating that we have reached a point of saturation in our search.

Several of the identified challenges can be linked to different methodological choices, indicating the need to discuss the implementation of standards as it could help to enable future harmonization within the field. The need for harmonization was further confirmed during the interviews, where a consensus on future calculations, as well as a more transparent methodology, was requested [30]. The standard ITU-T L.1450 [26], as well as the type III environmental declaration Environmental Product Declaration (EPD) and associated Product Category Rules (PCR), were furthermore discussed [38,39] as ways that could fill an important role in harmonizing the research field and increasing the transparency and comparability of studies. However, it was brought up in one of the interviews as a problem that the implementation and usage of standards and/or set rules will limit the degree of freedom of the practitioner [25], thus possibly also hindering future development. Another respondent furthermore noted that something as complex as standards or set product category rules might not even be necessary if seeking to harmonize the field of research [31]. It was instead suggested that the sector should strive for a better understanding of the most important influencing factors and the linked uncertainties [28]. Other participants noted that the increased involvement of telecom operators is a prerequisite for developments within the field [31] and that future harmonization is a question of maturity and that the sector need a few years to rid itself of the anomaly [25]. As a result, based on the types of challenges identified and what emerged as a common view in the interviews, we suggest that future research on the topic should not result in a fixed set of rules, but rather in a commonly accepted methodology, which in turn could enable future harmonized life cycle assessments of network traffic.

We have presented several research approaches that address the challenges in part but were not able to find solutions that fully cover the identified problems on a satisfying level. Future research is therefore needed in many areas. The two preferable system boundaries (Figure 2, alternatives C and E), as well as the two more reoccurring data collection methods (top-down and bottom-up), require more research to enable an established approach within the research field. Furthermore, even though being deemed solvable in due time, the overall low transparency when studying network transmission needs further attention. The choice of either limiting the validity of LCAs to one year of reference or studying the energy efficiency gains need to be explored further due to differing opinions, as well as the allocation challenge identified in data centers, which was not disclosed in detail during the interviews. Several areas in need of further development were also identified which have no direct linkage to the presented research approaches. Flaws were identified in relation to the top-down and bottom-up data collection methods, and more knowledge within the area of LCA, further sensitivity analyses, and a better base for calculations have all been deemed topics of high importance and in need of further attention.

The contribution and novelty of this paper is the attempt to provide a systematic and comprehensive overview of the existing challenges when seeking to measure the life cycle impact of network traffic and to propose solutions to said challenges. Where previous studies have focused on one or two challenges, often based on own experiences from single case studies, we collected a broader range of challenges by both reviewing the literature and interviewing experts from industry and academia about their views and experiences. By providing a foundation of challenges in need of further research, our hope is that this paper will act as a starting point and aid future work within the field, for future studies to originate from or to be inspired by. By further advancing the research, our intent is to contribute to harmonizing LCA estimates of the environmental impact of network traffic.

5. Conclusions

This paper sought to identify challenges when assessing the life cycle environmental impact of network traffic, as well as to propose how these challenges could be addressed. The results showed eight key challenges within the areas of system boundaries, data collection methods, energy intensity metrics, transparency and data availability, allocation procedures, age of data, assumptions within the LCI phase, and limited coverage of impact categories. Approaches that addressed said challenges were proposed, but further research is needed in several areas. The current challenges identified in this study can be a useful starting point for future research on the topic to further advance the harmonization of LCA estimates of the environmental impact of network traffic. In conclusion, we recommend that the sector further seek to investigate the most important influencing factors when assessing LCAs of network traffic, as well as agree upon a commonly accepted methodology with several parameters of significance to enable future harmonized studies.

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Appendix A

Written Interview Guide
Date: Name of the interviewee:
Introductory questions What is your position at . . . ? How long have you been working there? What are your responsibilities? What is your previous experience with network traffic and its environmental impact?
System boundaries Why do you think the system boundaries differ between many studies? Why are subsystems within the ICT sector and Internet network sometimes defined differently? Why do you think the terminology differs? Do you agree with the illustration of possible system boundaries? What changes could be made to improve the accuracy of the image? Which alternative or combination of subsystems do you think would be most optimal to include, use and measure? Why?
Data collection methods Which methodological data collection methods are you familiar with? Which data collection method would be most optimal to use? Why?
Electricity intensity metrics When measuring electricity intensity, do you agree that kWh/GB is the preferable option? Why/Why not? What is your opinion about using a unit more specifically linked to time? What other alternatives could the LCA practitioner?
Transparency What are the reasons behind the currently low transparency within the sector? How could this issue be solved? Could one implement a separate, third-party entity?
Age of data Is it possible to limit the validity of the results to one year of reference? If no, why? Would it be possible to compare the results of the same year of reference? If no, why?

Written Interview Guide
Allocation procedures Where do allocation occur, and which areas are most problematic in your opinion? Why? What would be the best approach in your opinion? Why?
Limited coverage of impact categories Why has only the carbon footprint been accounted for so far in the most research literature?
What are other areas that should be given more focus, in your opinion?
Varied user practices How does one make sure that future LCAs use the same methodology? Have you heard about type III environmental declarations? Could product category rules or anything similar be used as an appropriate framework?
Other Have you identified other problems not mentioned previously during the interview? If yes, what? Is there anything you would like to add? If yes, what?

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